INTERPHASE MOMENTUM, HEAT AND MASS TRANSFER IN STEADY-STATE TURBULENT HIGH-TEMPERATURE JETS WITH PARTICLES

O.P. Solonenko
Institute of Thermophysics, Siberian Branch of the USSR Academy of Sciences, Novosibirsk-90, 630090, USSR

ABSTRACT

The suggested mathematical model for a free turbulent jet of high-temperature gas with admixed monodisperse particles subjected to the processes of heating, melting and evaporation, can be used as a basis for theoretical and experimental studies of the interphase momentum, heat and mass transfer in heterogeneous plasma jet flows.

1. INTRODUCTION

Two-phase turbulent jet flows with admixed droplets of sprayed liquid or solid particles in the suspended state, have been extensively used in various fields of science and engineering. Their dynamic peculiarities are different, e.g. a turbulent two-phase jet with admixed liquid drop particles can be obtained by the injection of a jet of decomposing liquid into the gas medium. A jet with solid particles is obtained only through gas-injected admixtures.

Nowadays numerous fundamental theoretical and experimental data are known from the literature [1,2,etc.], concerning the processes of momentum and mass transfer in steady-state turbulent isothermal two-phase jet flows. But, although the high-enthalphy heterogeneous jet flows find significantly more extense practical application (plasma technology, jet and power mechanical engineering, rocketry, etc.), no mathematical model is as yet known, which would sufficiently completely describe gasdynamic peculiarities and the interphase transfer accounting for such important factors as dynamic and thermal nonequilibrium of phases in the averaged and pulsation motion, the effect of admixed particles on the jet turbulence, the effect of phase transformations on the gas flow parameters, etc.

Few literature data [3,4,etc.] cannot clarify the problem. Moreover, at the present state of the art in the study of two-phase flows and, in particular, of high-enthalphy heterogeneous jets, it is necessary to aprobe and test experimentally the applicability of various equations of motion and energy of multiphase media.

The present study was aimed at the numerical modelling of a thermally local-equilibrium plasma jet flow with admixed monodisperse particles with taking into account their heating, melting and evaporation, and it is a continuation of the previous work [5]. The description was based on the general averaged motion and energy equations for turbulent multiphase flows [6,7], obtained according to the method of space and time averaging of the initial balance integral relations.

2. RESULTS

Consider a jet flow of high-enthalphy gas ejected from an annular nozzle orifice d_n into the gas medium of the same composition. We will restrict ourselves to two axisymmetric methods of powder injection into the jet: 1) inside the nozzle channel and 2) at some angle β to the jet axis through an annular slot of the width h directly adjoining the nozzle orifice (Fig. 1,a,b).

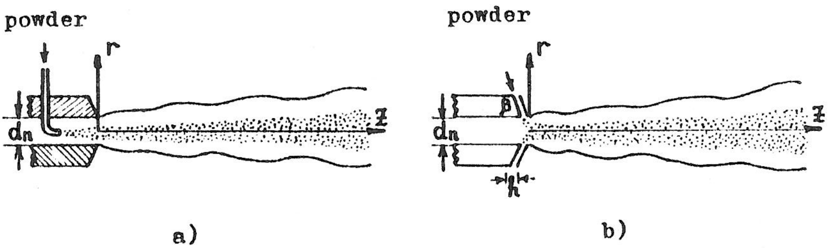

Fig.1. Schematic representation of the jet flow.

The powder is assumed to be monodisperse and its thermophysical properties to be the known temperature functions. The effect of the carrier gas due to its small discharge is neglected. In what follows the following assumptions will also be used: 1) the jet flow is isobaric, steady and satisfies the conditions of local thermodynamic equilibrium; 2) the turbulent transport of substance along the jet axis is significantly lower than the convective transfer, i.e, the boundary layer approximation is valid; 3) the terms of the energy equation characterizing mechanical motion are small compared with the heat terms; 4) the local temperatures and velocities for a plasma-generating gases and particle vapours are similar; 5) the effect of gravitational forces on the particles motion can be neglected (if this effect does not disturb the axial symmetry, it can readily be taken into account); 6) the particles heating is gradientless; 7) the evaporation of particles in the temperature range from melting to boiling can be neglected, which holds for the metals whose vapours are low-pressure (this assumption is insignificant, since particles evaporation in the above temperature range can be taken into account, e.g. like in [8]; 8) the direct interaction between particles can be neglected; 9) the processes of particles vapour condensation are not taken into consideration.

The indices "p", "n", "g", and "f" will be given for the parameters of particles (irrespective of their solid or liquid states), their vapours, plasma-generating gas and gas-vapour mixture, respectively.

Taking into account the above-said and having separated equations 6,7 to stages, we will obtain the following system of equations of:

- mass balance, momentum and heat of particles

$$\frac{D_p^*}{d\tau}\rho_p S_p = -G_p^{(1)} , \tag{1}$$

$$\frac{D_p^*}{d\tau}\rho_p S_p w_{zp} = F_{zp} - w_{zp} G_p^{(1)} , \tag{2}$$

$$\frac{D_p^*}{d\tau}\rho_p S_p w_{rp} = F_{rp} - w_{rp} G_p^{(1)} , \tag{3}$$

$$\frac{D_p^*}{d\tau}\rho_p S_p h_p = Q_{pc} + Q_{pr} - Q_{pf}^{(1)} - Q_{pf}^{(2)} ; \tag{4}$$

- mass balance of particle vapours and plasma-generating gas

$$\frac{D_f^*}{d\tau}\rho_n S_n = G_p^{(1)} , \tag{5}$$

$$\frac{D_f^*}{d\tau}\rho_g S_g = 0 \quad ; \tag{6}$$

- balance of momentum, turbulence and heat energy for gas--vapour mixture

$$\frac{D_f^*}{d\tau}\rho_f w_{zf} = -F_{zp} + w_{zp} G_p^{(1)} + \frac{1}{r}\frac{\partial}{\partial r} r \mu_f \frac{\partial w_{zf}}{\partial r} , \tag{7}$$

$$\frac{D_f^*}{d\tau}\rho_f k_f = K_f^{(+)} - K_f^{(-)} - K_p^{(-)} , \tag{8}$$

$$\frac{D_f^*}{d\tau}Q_f = \frac{1}{r}\frac{\partial}{\partial r} r S_f \lambda_f \frac{\partial t_f}{\partial r} - Q_{pc} - Q_{pr} + c_{pn} t_p G_p^{(1)} ; \tag{9}$$

- relation between bulk concentrations of the components

$$S_p + S_n + S_g = 1 . \tag{10}$$

In (1)-(9) the following nomenclature is used S_ℓ, ρ_ℓ, $w_{z\ell}$, $w_{r\ell}$, h_ℓ are the bulk concentration, density, longitudinal and transverse velocity components and enthalphy corresponding to the l-th component ($\ell = p, n, g, f$); $G_p^{(1)}$ is the power of mass flow of particles due to their evaporation; F_{zp}, F_{rp} are the projections of the force acting on the particles on the part of the gas-vapour mixture; Q_{pc}, Q_{pr} are the convection and radiation heat fluxes characterizing the heat transfer between the disperse phase and the gas-vapour medium; $Q_{pf}^{(1)}$, $Q_{pf}^{(2)}$ are the intensities of the heat fluxes consumed for melting and evaporation of the particles; μ_f, λ_f are the coefficients of dynamic viscosity and thermal conductivity of the gas-vapour mixture; $K_f^{(+)}$, $K_f^{(-)}$ are the generation and dissipation of the turbulence energy $k_f = [\langle w_{zf}''^2\rangle + \langle w_{rf}''^2\rangle + \langle w_{\varphi f}''^2\rangle]/2$ of the gas-vapour mixture; $K_{pf}^{(-)}$ is the additional dissipation of the turbulence energy determined by the particles inertia in the averaged and pulsation motions; $\rho_f = \rho_n S_n + \rho_g S_g$, where $S_f = S_n + S_g$; $C_{p\ell}$ is the specific heat capacity at constant pressure characterizing the l-th component; $Q_f = \rho_n S_n h_n + \rho_g S_g h_g$ is the heat content of the gas-vapour mixture. $D_\ell^*/d\tau$ is the differential operator

$$\frac{D_\ell^*}{d\tau}\psi \equiv \frac{\partial}{\partial z}\psi w_{z\ell} + \frac{1}{r}\frac{\partial}{\partial r} r\left\{\psi w_{r\ell} + \langle \psi'' w_{r\ell}''\rangle\right\}, \quad \ell = p, f \tag{11}$$

where ψ is the arbitrary scalar substance; two primes mark the pulsations of the respective values; $\langle\cdots\rangle$ marks the space-time averaging. Equations (1)-(9) are written in the cylindrical system of coordinates, whose origin is localized at the nozzle center and the Z-axis coincides with the axis of the jet.

Force interaction between particles of the mixture and gas-vapour medium at $\rho_f \ll \rho_p$, which is the case for the flow under consideration, is represented as:

$$F_{ip} = \frac{3}{4} C_f(Re_p, M_p)\rho_f \frac{S_p}{d_p} \cdot |\vec{w}_f - \vec{w}_p| \cdot (w_{if} - w_{ip}) , \tag{12}$$

where $i = z, r$ and the calculation of the drag coefficient is based on the relation [10] accounting for the effects of the medium inertia and compressibility; d_p is the particles diameter.

The convective heat flux to the particles can be represented as [11] :

$$Q_{pc} = 6 S_p \lambda_f Nu_p (t_f - t_p)/d_p^2 , \tag{13}$$

where

$$Nu_p = 1 + 0.55\,Re_p^{0.5}\,Pr^{0.33} + 1.8\sqrt{Re_p''} \quad . \tag{14}$$

In (13)-(14) t_f, t_p are the local temperatures of the gas-vapour mixture and particles; $Re_p = \rho_f d_p \cdot |\vec{w}_f - \vec{w}_p| / \mu_f$ and $Re_p'' = \rho_f d_p \sqrt{2k_f} / \mu_f$ are the Reynolds numbers for the relative motion of phases in the averaged and pulsation motions, respectively.

The radiation heat transfer between particles and medium is estimated [12] as:

$$Q_{pr} = 6 S_p \alpha \sigma (t_f^4 - t_p^4)/d_p^2 \ , \tag{15}$$

where $\alpha(t_p) = \varepsilon + \gamma t_p$ is the absorbability; σ is the Stefan-Boltzmann constant and ε, γ are the constants.

Equations to describe $Q_{pf}^{(1)}$, $Q_{pf}^{(2)}$, $K_f^{(+)}$, $K_f^{(-)}$, $K_p^{(-)}$ and melting of the particles were taken from the previous work [5]. Equations (1)-(9) were closed using the semi-empirical turbulence hypotheses [5,13]. Besides the previously used equation for the turbulent analog of the Shmidt number Sc_p, we have used the equation

$$1/Sc_p = (1 - e^{-\eta})\left[1 - \frac{1}{\eta}(1 - e^{-\eta})\right] \ , \tag{16}$$

where $\eta = c\,T_L/T_p$; $T_L = L/\sqrt{2k_f}$ is the Lagrange time scale of the turbulence; $T_p = \rho_p d_p^2/(18\,\mu_f)$ is the characteristic time of the particle dynamic relaxation and c is the constant whose numerical value is determined via the correlation of calculated and experimental concentration distributions of the disperse phase in the jet cross sections.

The constructed mathematical model of the free steady jet flow of high-enthalphy gas with admixed metal particles subjected to heating, melting and evaporation processes, was used as a basis for the theoretical and experimental studies of the interphase momentum, heat and mass transfer in heterogeneous plasma jet flows. Some calculation data on the behaviour of metal powders in jet flows which are of interest for plasma sprayed coatings preparation, were described elsewhere[5]. Here we describe the results of the aprobation of the suggested model for several model jet flows with admixed disperse particles.

REFERENCES

(1) G.N. Abramovich, S.Yu. Krasheninnikov and A.N. Sekundov, "Turbulent Flows in Interaction of Bulk Forces and Nonselfsimilarity" (Mashinostroenie, Moskva, 1975).

(2) M.K. Laats and F.A. Frishman, "Transport Processes in Turbulent Shear Flows" (Akad, Nauk. ESSR, Tallin, 1973).

(3) P.O. Hedman and L.D. Smoot, AIChE J., 21, 372 (1975).

(4) S.A. Panfilov, V.S. Simkin, I.K. Tagirov and Yu.V. Tzvetkov, "Physico-Chemical Computer Studies in Metallurgy and Metal Technology" (Nauka, Moskva, 1975).

(5) O.P. Solonenko, Proc. VIII All-Union Conf. on Low-Temperature Plasma Generators, Part III (Inst. Thermophysics, Novosibirsk, 1980).

(6) F.I. Frankl, Dokl. Akad. Nauk SSSR, 92, 247 (1953).

(7) A.K. Dyunin, Yu.T. Borshchevsky and N.Ya. Yakovlev, "Fundamentals of Multi-Component Flows Mechanics" (Sib. Otd. Akad. Nauk SSSR, Novosibirsk, 1965).

(8) O.N. Lebedev and O.P. Solonenko, Izv. Sib. Otd. Akad. Nauk SSSR, Ser. tekh. nauk, 3, 66 (1976).

(9) I.P. Ginzburg, "Friction and Heat Transfer in Gas Mixtures Flows" (State University, Leningrad, 1975).

(10) D.J. Karlson and R.F. Hoglund, AIAA J., 2, 11 (1964).

(11) R.S. Tyulpanov, J. Eng. Phys., 31, 619 (1976).

(12) A.A. Uglov, Yu.N. Lokhov, A.G. Gnedovetz, Dokl. Akad. Nauk SSSR, 244, 354 (1979).

(13) H. Danon, M. Wolfshtein and G. Hetsroni, Int. J. Multiphase Flow, 3, 323 (1977).

(14) O.N. Lebedev and O.P. Solonenko, Izv. Sib. Otd. Akad. Nauk SSSR, Ser. tekh. nauk, 13, 98 (1978).